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 ENVIRONMENTAL  
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# Investigation of exhaled pollutant distribution in the breathing microenvironment in a displacement ventilated room with indoor air stability conditions

Xiaorui Deng<sup>1,2</sup>, Guangcai Gong<sup>1,2,\*</sup>

<sup>1</sup>Department of Civil Engineering, Hunan University, Changsha 410082, China

<sup>2</sup>Key Laboratory of Building Safety and Energy Efficiency, Ministry of Education, Hunan University, Changsha 410082, China

## ARTICLE INFO

### Article history:

Received 26 December 2019

Revised 18 June 2020

Accepted 18 June 2020

Available online 27 July 2020

### Keywords:

Displacement ventilation

Indoor air stability

Human breathing

microenvironment

Personal exposure

## ABSTRACT

This study experimentally studied the dispersion of exhaled pollutant in the breathing microenvironment (BM) in a room equipped with a displacement ventilation (DV) system and indoor air stability conditions (i.e., stable and unstable conditions). The vertical temperature differences and the carbon dioxide (CO<sub>2</sub>) concentration in the BM were measured. Results show that when DV is combined with the stable condition (DS), pollutant tends to accumulate in the BM, leading to a high pollutant concentration in this region. Whereas, when DV is combined with the unstable condition (DU), pollutant diffuses to a relatively wider area beyond the BM, thus the pollutant concentration in the BM is substantially reduced. Moreover, increasing the flow rate can reduce the pollutant concentration in the BM of the DS but yields little difference of the DU. In addition, personal exposure intensity increases with time, and the DS has a relatively higher increase rate than DU. The results suggest that indoor air stability will affect the performance of DV systems. DS will lead to a higher health risk for people when they stay in the indoor environment with pollutant sources, and DU is recommended for minimizing pollutant level in the BM in order to reduce the pollutant concentration and providing better air environments for the occupants.

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## Introduction

Air quality in the indoor environment is essential to the occupant health, especially in the breathing microenvironment (BM) around the human body, as they are exposed to this area directly by inhalation (Han et al., 2017). There are many sources of pollutants in indoor environments, the most common of which are the occupants themselves (Zhou et al., 2017). For example, the breathing activities generate bio-

aerosols that may carry bacterias, viruses, and other substances (Melikov, 2015). If not being dispersed effectively from the BM, these bio-aerosols might be re-inhaled by the occupants, causing adverse health impacts, such as contagious infectious diseases, or even worse, cancer (Douwest et al., 2003). In order to protect the occupants from being infected, the concentration of the exhaled pollutants in the BM should be controlled at an acceptable level.

Normally, ventilation systems are implemented in the built environment either in a natural way or a mechanical way

\* Corresponding author.

E-mail: [gcgong@hnu.edu.cn](mailto:gcgong@hnu.edu.cn) (G. Gong).

to remove pollutants and regulate indoor air distribution (Coffey and Hunt, 2007). One of the mechanical ventilation methods is displacement ventilation (DV), where cool fresh air is supplied at or near the floor level and creates an upward air movement when the supplied air meets the heat sources in the room. As a result, the temperature is well mixed in the upper room and thermally stratified in the occupied area. DV is regarded as an efficient ventilation method when compared with the traditional mixing ventilation (Awbi, 2015). However, the associated vertical temperature differences of the DV are often considered as a disadvantage of DV (Melikov and Nielsen, 1989), because it can lock the exhaled flow in a finite layer (Bjørn and Nielsen 2002; Gao et al., 2008), in which the exhaled flow would penetrate for a long distance horizontally (Qian et al., 2006). This exhalation layer might possibly contain virus or bacteria (Olmedo et al., 2012) that may increase the possibility of the transmission of infectious diseases. Especially in some indoor environments, such as the hospital ward, DV cannot provide reliable protection against airborne cross-infection to the pathogen (Popio-Lek et al., 2012). Thus advanced air distribution method is critically needed for the purpose of reducing personal exposure to the exhaled pollutants in the BM in a displacement ventilated room.

The formation of the indoor vertical temperature gradient is a function of heat conduction, convection and radiation in the built environment (Li et al., 1992), so vertical temperature differences can not only be found in DV systems but also in other Heating, Ventilation, Air-Conditioning systems (HVAC). For example, the hybrid system of radiant panel and DV (Choi et al., 2019), the hybrid system of chilled ceiling and DV (Schiavon et al., 2012), the radiant heating/ceiling panel system (Li et al., 2015; Olesen et al., 2016), floor cooling system (Zhou, 2019), and air carrying energy radiant air-conditioning system (Peng et al., 2019). However, most of them focused on the occupant thermal comfort (Yu et al., 2007; Möhlenkamp et al., 2018; Tomasi et al., 2013; Melikov and Nielsen, 1989; Hashiguchi et al., 2010; Melikov et al., 2005; Cheong et al., 2007), and few have developed models for predicting the pollutant concentration distribution (Choi et al., 2019).

In the last decade, the effect of indoor vertical temperature differences on air distribution and pollutant transport has raised concern. Gong et al. (2010) defined this vertical temperature difference as indoor air stability and pointed out that it can be used as a measure to show the indoor air's ability to inhibit air parcel's vertical motion. Indoor air stability is classified into three conditions according to different vertical temperature gradients in the indoor environment, namely, stable, neutral and unstable. In the stable condition, where the vertical temperature increases with height, the buoyancy force of the air parcel will inhibit its vertical movement. In the unstable condition, where the vertical temperature decreases with height, the intensified instability of the room air will promote the entrainment of the pollutant with the surrounding air and thus enhance the vertical movement of the exhaled pollutant. Xu et al. (2015a) found that the concentration decay of pollutant from respiration activities was greatly dependent both on the indoor air stability and the metabolic level, so they suggested that sufficient consideration of indoor air stability conditions should be taken when studying the pollutant trans-

mission from the breathing process. A recent study (Gong and Deng, 2017) pointed out that indoor air stability can greatly affect the dispersion of the exhaled flow in the BM. They found that in the stable environment, the exhaled flow tended to retain the initial inertia force and the majority of the exhaled flow would stay in the exhaled mainstream. In the unstable environment, the exhaled flow mixed intensely with the surrounding air, so it quickly deviated from the original direction. Zhou et al. (2017) examined the characteristics of exhaled flow transport in a thermally uniform environment (neutral condition) and in a thermally stratified environment (stable condition) and found the same results as Gong and Deng (2017) reported that the exhaled flow dispersed freely in a neutral condition but confined at the lock-up layer in a stable condition. In addition, it has been found that indoor air stability could affect the performance of ventilation in a microgravity environment (Deng and Gong, 2020) and in a lunar-gravity environment (Wang et al., 2014).

The above literature reviewed showed that the exhaled pollutant transport in the BM was the result of a complex interaction among the breathing activity, the ventilation method, and indoor air stability conditions. The purpose of this study was to analyze the pollutant distribution in the BM in a displacement ventilated room when combined with different indoor air stability conditions, namely, DV combined with the stable condition (DS) and DV combined with the unstable condition (DU). Exposure intensity under different combinations were evaluated. A radiant air-conditioning system was used as a complementary system with DV. Each experimental period lasted 30 min in order to obtain the general characteristics of pollutant distribution under different combinations.

## 1. Methods

### 1.1. Experiment setup

The experiments were carried out in a full-scale test room equipped with an air-carrying-energy radiant air condition system (Fig. 1a) at Hunan University. The air-carrying-energy radiant air condition system is a novel type of radiant air conditioning that works energy-efficiently in reducing the condensation risk and providing thermal comfort (Peng et al., 2019; Peng et al., 2020; Gong et al., 2017). The dimension of the test room was 4.00 m (length) × 3.80 m (width) × 2.40 m (height). Fig. 1b shows the layout of the DV system. A wall-mounted air supply vent was located at the bottom of the side-wall, with a dimension of 0.16 m × 0.26 m. The exhaust vent was of the same size as the supply vent and was installed near the top of the opposite wall. Two return-vents (return h and return c), with a dimension of 0.28 m × 0.58 m were mounted on the middle of one of another sidewall. The sidewalls of the room were well-insulated and can be considered to be adiabatic. When the radiant air conditioning system was in the heating mode, return h was open and return c was closed; when the radiant air conditioning system was in the cooling mode, return c was open and return h was closed.

Room temperature was controlled by the air-carrying-energy radiant air condition system installed above the ceiling and four electric blankets on the floor. The stable condi-